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Correlations of clouds, cosmic rays and solar irradiation over the Earth

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ABSTRACT

It is becoming apparent that the correlation of clouds at different altitudes with cosmic rays and solar activity is a matter of complexity. Specifically, evidence has been presented favouring particular regions of the Earth having positive or negative correlations of cloud cover with respect to cosmic rays and to solar irradiation.

In this work we examine the evidence critically from several standpoints and conclude that the evidence for a negative correlation of low and a positive correlation for middle cloud cover with solar irradiance (as measured by UV) over a significant fraction of the Earth (20–30%) is good. No other claimed correlations are supported.

1. Introduction

The apparent correlation of low level cloud cover (LCC) with cosmic rays (CR) and/or solar irradiance (SI) has been described by a number of authors (Svensmark and Friis-Christensen, 1997; Pallé Bago and Butler, 2000; Marsh and Svensmark, 2000; Svensmark, 2007; Harrison and Ambaum, 2008). The satellite cloud measurements came from the ISCCP D2 IR data (Rossow and Schiffer, 1999). These results have been criticised for a number of reasons. Firstly it was pointed out (Kristjánsson et al., 2002) that the correlation is much less evident in the day time ISCCP data than in the IR data. It was further pointed out (Udelhofen and Cess, 2001) that, if there is a correlation present, it is different in cloud cover measured over the USA from a different source than the global average of the ISCCP D2 IR data. The structures in the data used to deduce the correlations have also been criticised as probably instrumental artefacts (Norris, 2000). Such artefacts could account for $\sim 30\%$ of the signal but not all of it (Rossow, 2009). We assume, therefore, that there is an effect to investigate and we discount all the criticisms in order to try to establish to what degree the reported correlations are real.

The importance of such a correlation, if real, is that it could make a significant contribution to the radiative forcing responsible for global warming (Marsh and Svensmark, 2000; Svensmark, 2007). The proposed causal connection between LCC and CR has been treated with some scepticism (Laut, 2003; Pallé, 2005; Lockwood and Fröhlich, 2007; Sloan and Wolfendale, 2008). The correlation with CR was established using observations in solar cycle 22. The corresponding structures in the globally averaged cloud amount in solar cycle 23 which has ended recently are much less apparent.[1] The importance of regional correlations rather than the use of global cloud data was first pointed out by Pallé et al. (2004) and by Usoskin et al. (2004). Such position dependent correlations between the LCC, middle cloud cover (MCC) and high cloud cover (HCC) with both CR and SI were then studied in more detail (Voiculescu et al., 2006) using data in cycle 22 and part of cycle 23.

In this paper we describe a study of these reported regional correlations. In previous publications we have attempted to find evidence to corroborate the claimed correlation between CR and LCC in the globally averaged data. Firstly, we searched for a dependence of the modulation of the LCC on magnetic latitude (Sloan and Wolfendale, 2008) since the ionisation from CR is expected to show such a dependence. Then we looked to see if a magnetic latitude dependence could be seen in stratiform clouds since these are expected to be more sensitive to ionisation than cumuliform clouds (Erkykin et al., 2009a). Further atmospheric ionising events such as the nuclear weapons tests in the 1960s, the Chernobyl reactor accident in 1986, etc. were examined to see if the released ionisation could be correlated with changes in the LCC in the region of the ionising event (Erkykin et al., 2009b). In none of these investigations could corroborative evidence be found for the proposed correlation between CR and LCC. In view of the possible significance to the question of global warming, we continue in this paper to search for evidence to corroborate the effect concentrating on the local regions where there has been an identified correlation by Voiculescu et al. (2006).

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[1] See the graph of IR low-level clouds at http://isccp.giss.nasa.gov/climanal7.html.

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The local regions of correlations between LCC and CR and between LCC and SI are shown on the maps in Voiculescu et al. (2006). The regions cover a fraction of the globe. These regions are examined here in order to attempt to establish the level of the physical significance of the correlations with each of CR and SI. The properties of the correlations examined include the multiplicities of occurrence, their clustering on the Earth and whether or not the clustering appears to correlate with meteorological features such as Hadley cells (Hadley, 1735). In addition, we look to see whether or not the cloud cover (CC) in each region shows the appropriate structures in both solar cycle 22 (1984–1995) and the completed cycle 23 (1995–2007). Each property examined is listed in Table 1.

2. The maps given in Voiculescu et al. (2006)

The cloud data in Voiculescu et al. (2006) are treated in geographical grids of $5^{\circ} \times 5^{\circ}$ cells (2592 in total) and in the three altitude ranges given by the ISCCP: HCC, altitude >6.5 km; MCC, altitude 3.2–6.5 km; LCC, altitude <3.2 km. The CR data are from the simulations in Usoskin and Kovaltsov (2006), of the ionisation of the atmosphere as a function of altitude and latitude. The proxy for SI data adopted are those for UV found by using the MgII core-to-wing index (obtained from NOAA Space Environment Center, http://www.sec.noaa.gov/data). Emphasis is laid on the UV rather than SI itself since the variability in SI over the 11-year cycle is almost entirely in the UV. We note in passing that this UV is absorbed at high levels in the atmosphere ($\simeq 40$ km) so that any change in the CC must be by an indirect mechanism—e.g. that given in Haigh (1996)—unlike the CR case where the effect is in situ.

It is well known that there is an inverse correlation between CR and either SI or the mean daily sun spot number (SSN) caused by the solar wind, the strength of which is related to both the SI and SSN. It is thought that the solar wind modulates the CR intensity. Fig. 1 shows modulation pattern for each of the CR, SI (through the UV as measured by the MgII index) and the SSN. The profiles are similar to each other and distinction between a positive CR correlation and a negative UV correlation must rely on other factors. Note that the difference between CR and UV is mainly that of a small time-lag which has a small cycle-to-cycle variability.

Table 1
Summary of properties of the correlation maps.

Correlation	Hits	$N(b \geq 5)$	C22,23	$b_{1/2}$
HCC UVp	64	3	Yes	$1.7^{+0.5}_{-0.3}$
HCC UVn	64	1	Yes	$2.3^{+1.3}_{-0.7}$
HCC CRp	29	1	No	$2.0^{+1.1}_{-0,5}$
HCC CRn	253	12	No	$3.0^{+0.7}_{-0.6}$
MCC UVp	304	12	Yes	$2.8^{+0.6}_{-0.5}$
MCC UVn	28	2	Yes	$2.2^{+1.5}_{-0.7}$
MCC CRp	45	3	No	$2.1^{+0.7}_{-0.5}$
MCC CRn	85	4	No	$2.5^{+0.7}_{-0.5}$
LCC UVp	15	1	No	$1.4^{+1.8}_{-0.2}$
LCC UVn	539	25	Yes	$4.7^{+1.4}_{-0.7}$
LCC CRp	203	11	No	$2.4^{+0.6}_{-0.4}$
LCC CRn	50	3	No	$2.4^{+1.3}_{-.07}$

'Hits' are the number of $5^{\circ} \times 5^{\circ}$ bins having the required correlation. b is the number of adjacent bins in a cluster. C22,23 Yes(No) means similar structure seen (not seen) in both solar cycles with more than 2 standard deviations significance (see Table 2).

3. Properties of the hits in the maps in Voiculescu et al. (2006)

3.1. Hit totals

The total number of cells for each category of correlation given in Voiculescu et al. (2006) is shown in the second column of Table 1. Inspection of this table shows that the total numbers of hit cells are characterised by one group with less than 100 hits (mean 48 and standard deviation 23) and another above 200 (mean 325 and standard deviation of 149). We assume that the group with the lower number is spurious. The assumption that this group is spurious is supported by the $b_{1/2}$ values (see Section 3.2), which are virtually the same, and equal to those for the correlations designated as induced by other clouds in Voiculescu et al. (2006). It would be unlikely that all cases should be the same insofar as the physical phenomena will be different for each case. For example, for HCC we are dealing with ice-crystals whereas it is mainly water droplets for LCC and either water or ice for MCC. Similarly the CR and UV mechanisms are quite different. The fractional coverage of the Earth's surface for the correlations with number of hits less than 100 is rather small.

3.2. Clustering of the hits

The published maps in Voiculescu et al. (2006) have been examined and for each one we identify 'clusters' of the $5^{\circ} \times 5^{\circ}$ bins which have the same correlation and which are in contact, vertically, horizontally or diagonally.

These clusters, containing b hits, can be regarded as putative geographical regions which have, for whatever reason, the same correlation. Following conventional astrophysical custom to search for clustering, we plot the number of clusters containing more than b hits, $N(>b)$ against b for each of the 12 situations: HCC, MCC and LCC and, for each CRp (i.e. positive), CRn (i.e. negative), UVp (i.e. positive) and UVn (i.e. negative) correlations. Fig. 2 shows the $N(>b)$ vs. b for the four categories with largest totals (HCC CRn, MCC UVp, LCC UVn and LCC CRp). In addition we give the other 'mechanism' (CR or UV) with the known inverse correlation referred to in Section 2 when it is one of the smaller totals. These distributions show roughly a power law behaviour with clusters sometimes covering large areas of the globe. We define the quantity $b_{1/2}$ as the value of b where $N(>b_{1/2}) = 1/2N(>0)$. Large values of $b_{1/2}$ mean that there are many big geographical areas having the same correlation. Small $b_{1/2}$ values are at risk of being due simply to noise. The values of $b_{1/2}$ are shown for each correlation type in the column 5 of Table 1. For hits generated randomly on the grid the distributions are somewhat steeper power laws with values of $b_{1/2} \sim 2$ for 400 hits.

Fig. 3 shows the values of $b_{1/2}$ for each classification of clusters. To assess the noise we use directly derived 'spuriously induced' correlations (by clouds in the other height ranges) identified in Voiculescu et al. (2006). These are related to the correlations between clouds and should be approximately independent of the UV or CR variation. The values are shown in Fig. 3 as the dashed lines. It will be noted that the majority of the $b_{1/2}$ values are close to the noise-values with the exception of the LCC UVn correlation.

3.3. Search for structures in solar cycles 22 and 23 in the correlation categories

The correlation regions in Voiculescu et al. (2006) were assigned using the cloud data from 1983 to 2004, ending before the completion of solar cycle 23. The ISCCP-D2 cloud data are now available up to December 2007 which allows a comparison of the

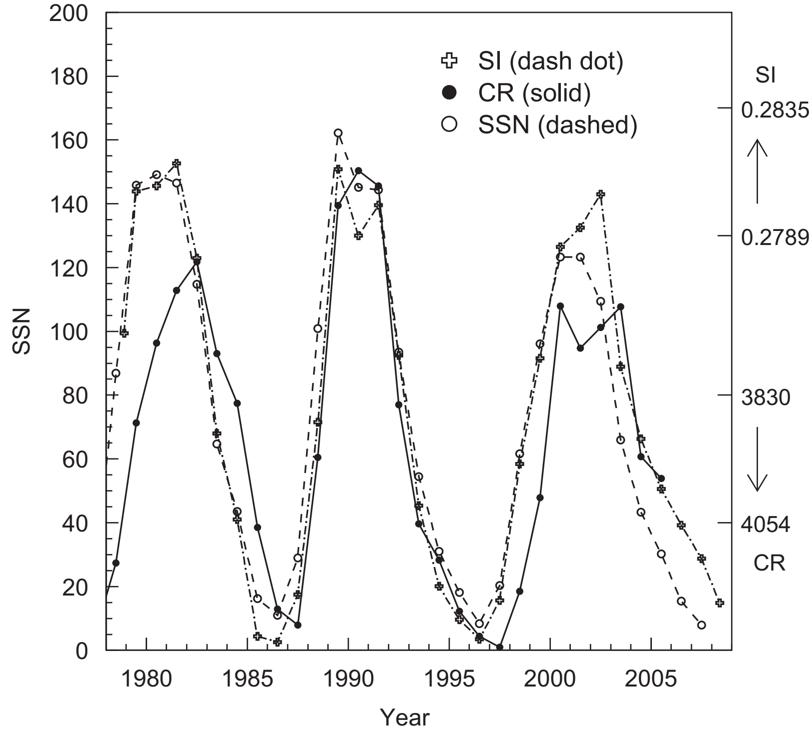

Fig. 1. Comparison of the time dependence of the Sunspot number (SSN) (available at http://www.ngdc.noaa.gov/stp/SOLAR/ftpsunspotnumber.html), Cosmic Ray Intensity (CR:Climax Neutron Monitor count rate, available at http://ulysses.sr.unh.edu/NeutronMonitor/neutronmon.html) and solar UV (available at http://www.sec.noaa.gov/data). The ordinates are, for SSN, standard sunspot numbers; CR (right hand axis lower scale NB increasing downwards); SI taken from UV intensity as measured by the MgII core to wing ratio (right hand axis upper scale. The values are yearly averages.

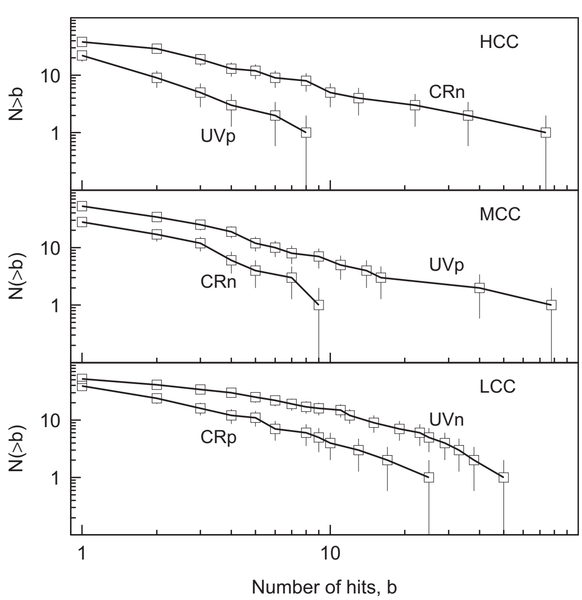

Fig. 2. Integral distribution of cluster sizes b, the number of touching $5^{\circ} \times 5^{\circ}$ bins having the same mode of correlation: upper panel HCC (CRn and UVp), middle panel MCC (CRn and UVp), lower panel LCC (CRp and UVn). The error bars are the Poisson statistical errors on each of the points which are correlated.

two complete solar cycles 22 (1986–1997) and 23 (1997–2007). Whilst there are differences between solar cycles, such differences in the changes to the SI and CR rates are minor. Hence any real effect of either CR or SI should be seen in both solar cycles.

To search for signs of solar activity in the cloud amount in each correlation category of Voiculescu et al. (2006) we follow the procedure adopted in Sloan and Wolfendale (2008) and fit a linear function plus a constant times the mean daily sun spot number (SSN) to the cloud cover data as a function of time (either LCC, MCC or HCC as appropriate). The constant represents the amplitude of the change (in percent change in cloud amount per unit daily SSN). Each fit is made separately for the solar cycles 22 and 23. Here we use SSN as a proxy for each of the changes in CR and UVI (see Fig. 1).

The fit is made minimising the mean square deviation of the measured points from the fit function. The value of χ^2 defined as

$$\chi^2 = \sum_i \left(\frac{d_i - F_i}{\delta} \right)^2 \tag{1}$$

was then deduced where d_i is the i th measured value of the cloud cover, F_i the value from the function and δ is the root mean square deviation of the points from the curve. The errors on the fitted parameters are obtained from the deviation of χ^2 from its minimum value as the parameter is varied (James, 1998). The fits are stable (tested by doing different fits omitting data points, etc.). A quadratic function has also been tried which gives similar results. The linear fits give a reasonable visual representation of the data so these have been adopted here.

Fig. 4 shows one of the fits in detail. The upper plot shows the yearly averaged LCC amount (solid points) together with the separate fits in each solar cycle (the smooth curves). The ISCCP-D2 IR data for the LCC show a tendency to fall with time and the MCC data to rise. The lower plot shows the data and the fit after subtracting the fitted linear trend from each. In this particular case both cycles 22 and 23 are clearly seen with equal decreases in both solar cycles within the error. We cannot exclude the possibility that this is caused by an artefact in the data which produces an autocorrelation between nearby data points. However, such an artefact seems implausible since it would

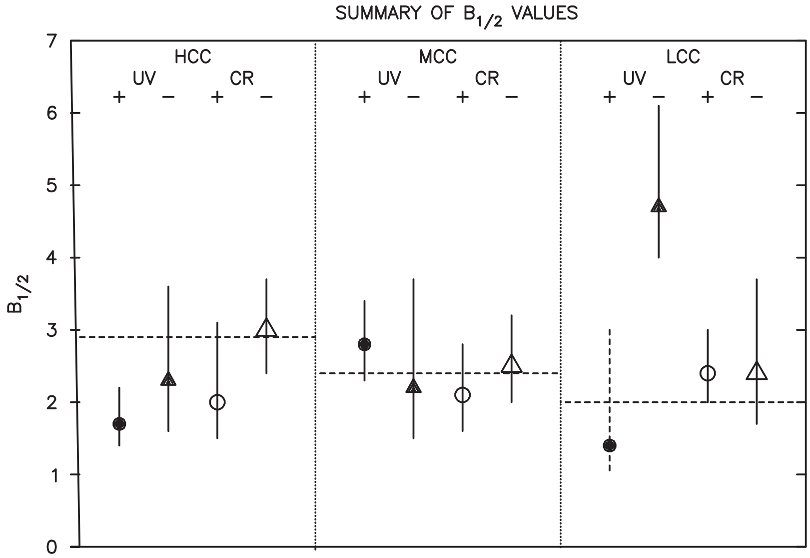

Fig. 3. Summary of $b_{1/2}$ values. Horizontal dashed lines show the estimate of the 'noise' measured from the induced correlations. Errors of $b_{1/2}$ value for LCC UVp correlation shown by dashed line are somewhat uncertain due to the very small number of hits (15).

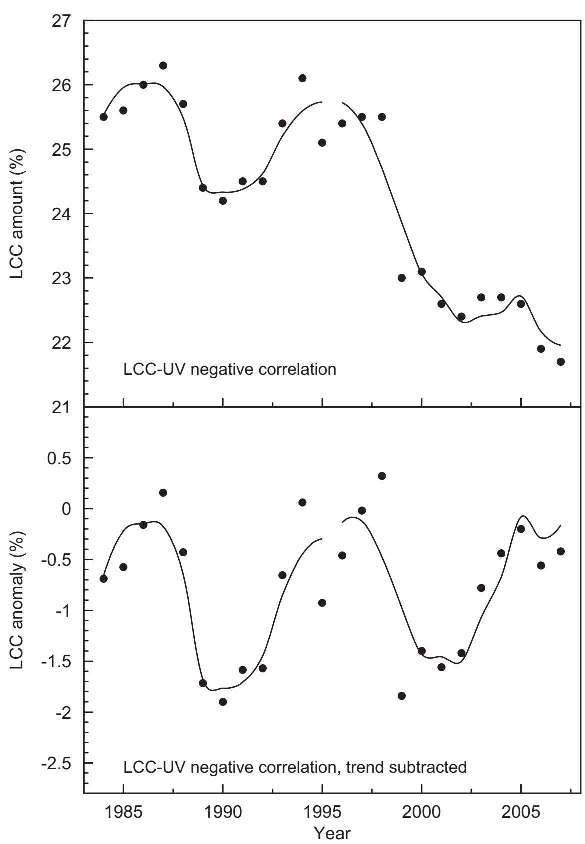

Fig. 4. The upper plot shows the yearly averaged LCC amount for all the LCC UVn regions (solid points) as a function of time with the fit in cycles 22 and 23 separately of the mean daily SSN plus a linear trend (smooth curves). The lower plot shows the anomaly i.e. the data and fit from the upper plot with the fitted linear trend subtracted.

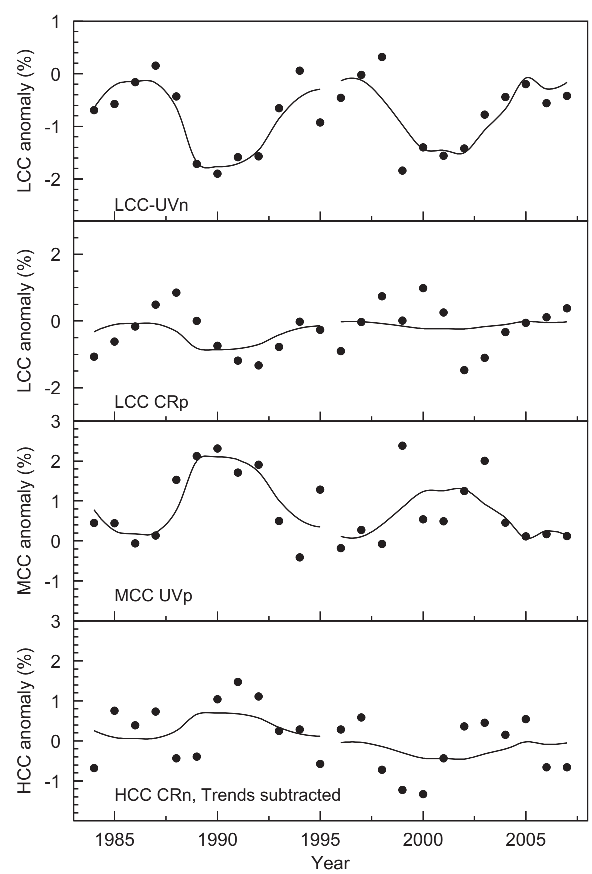

Fig. 5. CC anomalies (solid points) against time for the correlation categories with more than 200 hits. The smooth curves show the fits of the mean daily SSN to the CC data for each solar cycle separately after subtracting the fitted linear trends (see text and Fig. 4).

need to produce behaviour similar to the sunspot cycle and to affect only the distributions we have identified and be absent from all the others which have been tested (see below). To test if the effect could be caused by a statistical fluctuation, the points in the lower plot were randomised in time and refitted. This was done 10 000 times and equivalent cycle 22 and 23 structures occurred in three cases. Hence the probability that the structure in this plot is a statistical fluctuation is $\sim 3 \times 10^{-4}$. We therefore assume that the effect is a real correlation between the sun spot number and LCC in these regions.

Similar fits have been carried out for all other classes of correlations given in detail in Voiculescu et al. (2006). Fig. 5 shows the results for the correlation categories with more than 200 hits. Table 2 shows the measured changes in CC per unit change in mean daily SSN for each correlation separately in solar cycles 22 and 23. Adopting the criteria that the change is real if it is seen in each solar cycle with the same sign and with at least two standard deviations significance, Table 2 shows that both solar cycles are seen in the LCC UVn, MCC UVn, MCC UVp, HCC UVn and HCC UVp correlations. The LCC UVn and MCC UVp changes are of opposite sign which could indicate that the altitude of the low clouds increases slightly with solar activity transferring cloud from one layer to the other as the solar activity changes. Both solar cycles are not seen in the correlations with CR.

In column 4 of Table 1 the correlation categories where both solar cycles are seen with equal amplitude within the error and more than two standard deviations from zero are indicated by "yes" as deduced from Table 2.

4. Discussion of the results

It is assumed that the correlation categories with large numbers of hits (more than 200) in Table 1 are likely candidates for real correlations, as described above. The ones with larger numbers of hits are HCC CRn, MCC UVp, LCC UVn and LCC CRp. In the case of the latter two there are more than twice as many squares which show a strong negative correlation between the UV and LCC than in the case of CRp and LCC, so this is more likely be the most significant classification. The map showing the regions where these correlations occur is given in Fig. 6. Also shown as crosses are the locations for the complementary correlation (CRp) with more than 5 hits where complementary implies the other mechanism with opposite polarity. It is apparent that the crosses are close to the UVn areas. This is probably due to misidentification of UVn in the CRp maps (i.e. the general similarity of CR and UV in Fig. 1) since the UVn hits are more numerous than the CRp hits. For comparison similar maps are shown for MCC and HCC in Figs. 7 and 8.

All of the correlations with large numbers of hits show clustering of the hits with many containing more than 5 hits, indicating a large geographical extent of the clusters. Of these only MCC UVp and LCC UVn show similar significant structures in both solar cycles 22 and 23. Hence the correlations with SI seem to be better candidates for real correlations than any of the others.

Table 2
Change in CC per mean daily sun spot number in cycles 22 and 23 from the fits.

Correlation	Number of hits	Change cycle 22% CC per SSN	Change cycle 23% CC per SSN
HCC UVp	64	+0.006 ± .003	+0.008 ± .003
HCC UVn	64	−0.009 ± .003	−0.022 ± .005
HCC CRp	29	−0.017 ± .006	+0.014 ± .008
HCC CRn	253	+0.005 ± .004	−0.004 ± .005
MCC UVp	304	+0.014 ± .003	+0.011 ± .005
MCC UVn	28	−0.011 ± .004	−0.021 ± .005
MCC CRp	45	+0.002 ± .002	−0.000 ± .004
MCC CRn	85	+0.005 ± .004	+0.000 ± .003
LCC UVp	15	+0.005 ± .007	+0.025 ± .008
LCC UVn	539	−0.012 ± .002	−0.012 ± .003
LCC CRp	203	−0.006 ± .003	−0.002 ± .005
LCC CRn	50	−0.008 ± .008	−0.005 ± .008

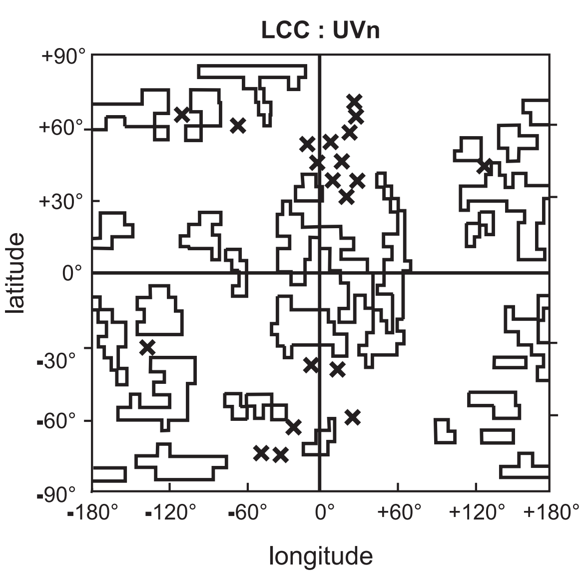

Fig. 6. Clusters having $b \geq 5$ for the LCC, UVn correlation ('boxes'). The crosses denote the approximate centres of $b \sim 5$ bins for LCC, CRp. Their closeness to LCC, UVn is attributed to misidentification arising from the closeness of the patterns in Fig. 1.

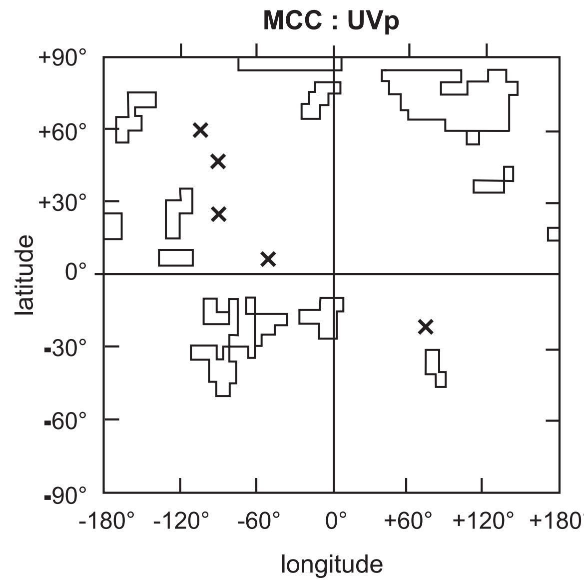

Fig. 7. As Fig. 6 but for MCC.

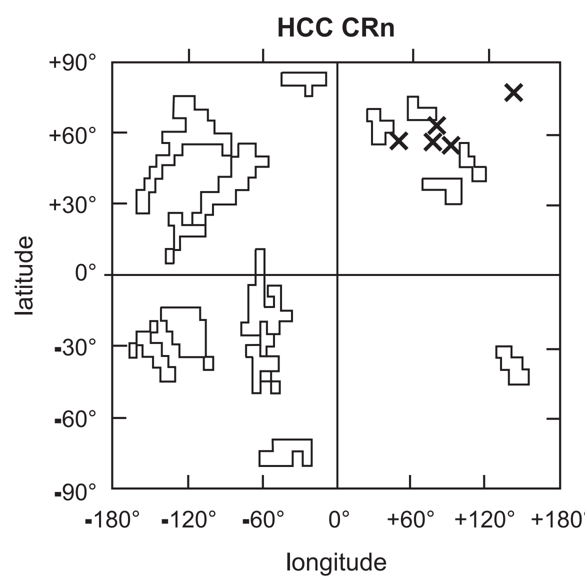

Fig. 8. As Fig. 6 but for HCC.

Interestingly, the LCC UVn has a significantly larger value of $b_{1/2}$ indicating greater geographical extent of the clusters than the other categories.

The most significant correlations are the MCC UVp and the LCC UVn correlations. None of the highly populated CR correlations (LCC CRp or HCC CRn) show similar structures in both solar cycles 22 and 23. Hence it seems that such reported correlations with ionisation from CR are not substantiated in this work.

The MCC UVp regions appear to be anticorrelated geographically with the LCC UVn regions in that overlaying the two maps gives fewer coincident regions (41 ± 6 in total) than overlaying randomly (average 59.4 coincidences). We have searched for connections between the geographical regions for each correlation with meteorological features such as Hadley cells. So far none has been found. The absence of a correlation of the patterns with any meteorological phenomena (17 maps of pressure, humidity, temperature, etc. were examined) is indicative of a possible subtlety with the mechanism, even if UV rather than CR is chosen.

5. Conclusions

The correlation regions identified in Voiculescu et al. (2006) between the ISCCP D2 IR data on cloud amounts, the cosmic ray ionisation and the solar irradiance have been examined. Of the 12 possible correlations only the negative correlation of low cloud and positive correlation of the middle cloud with the solar irradiance have all the attributes of real correlations. Each shows large numbers of hits, concentrated in extended geographical areas of the globe and giving similar changes in both solar cycles 22 and 23. The middle cloud correlation with the solar irradiance is in antiphase with equal and opposite variation to that in the low cloud within the errors of the measurements. The low level cloud cover is observed to decrease as the solar irradiance increases at solar maximum while the opposite is true for the middle level cloud cover. This could be due to the mean level of the cloud changing with solar activity so that low cloud tends to be reassigned to middle cloud at solar maximum with the opposite effect at solar minimum.

Examining the correlations with CR reported in Voiculescu et al. (2006), only the LCC CRp has large numbers of hits and is hence a candidate for a real correlation. However, this class fails our other criteria.

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